

Polarized Beam Jets

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Abstract

Handedness and a left-right asymmetry have been proposed as methods of probing the polarization of hard jets. If the analyzing powers for these observables are substantial they would provide useful tools for probing polarized hard scattering. This paper proposes that comparing these to the corresponding quantities in beam jets in polarized hadron-hadron collisions would be useful. These would shed light on the similarities and differences between the fragmentation of hard and soft jets. They would also suggest whether there is any useful possibility of measuring jet polarization. The left-right asymmetry of beam jets has already been measured and is large. But measurements of the handedness of beam jets have still to be done. They could be done in an upgraded HERMES detector at HERA.

1 Introduction

Observables have been defined that enable one to probe the spin of a quark initiating a jet. These are handedness [1, 2, 3], which provides a measure of quark helicity, and the shared jet effect [4, 5, 6], which is really a kind of left-right asymmetry and which measures a quark's transverse spin.¹ Such observables would be very useful for an experimental program of polarized hadron collisions at high energy, such has been proposed [8] for the Relativistic Heavy Ion Collider (RHIC) at Brookhaven—see, for example, the papers by Stratmann and Vogelsang [9] and Nowak [10].

Now, these observables are proportional to quark spin, but each with a constant of proportionality, an analyzing power, that is a property of the hadronization process in the jet. Unfortunately, these analyzing powers are non-perturbative quantities that cannot at present be predicted from QCD. Therefore it is highly desirable to measure the analyzing powers in advance of the proposed program of spin physics at RHIC; if either of them

¹Many of these ideas can be found in an article by Baldracchini et al.[7]

should happen to be substantial, there would be a substantial impact on the direction of experimental investigations.

The purpose of this paper is to propose some additional ways of gaining insight into the sizes of these analyzing powers, and in particular into their relative sizes. I observe that the bulk of events in a high energy hadron-hadron collisions are kinematically two jet events. Then the sheared jet and handedness observables can be defined in identically the same manner as for the jets resulting from a hard collision. Aside from their impact on the RHIC spin physics program, these measurements have an intrinsic interest as a probe of the mechanism by which soft beam jets are made.

So far, experimental observations have been made of the transverse spin observable in soft collisions [12, 13] and of handedness [11] in e^+e^- annihilation at the Z^0 ; the first gives a large result (tens of percent at large x_F) while the second has resulted in an upper bound of a few percent. The transverse spin effect in hard jets can be measured from jet-jet correlations in e^+e^- annihilation, as explained by Artru and Collins [6].

One purpose of the present paper is to complete the set of observables by suggesting measurement of the handedness of a spectator jet in a collision of a longitudinally polarized proton. Since there appear to be no suitable proton-proton experiments available, a second purpose is to show that the measurements can be made in the target fragmentation region of polarized electroproduction experiments (in particular at low Q^2). The HERMES [14] experiment appears particularly suitable.

Finally, I will comment on the implications of these measurements. If soft and hard jets are similar as regards their non-perturbative properties then one predicts a large sheared jet effect in hard jets, but one predicts a small handedness in soft jets. If these predictions are not verified by experiment then one has a clear demonstration of large differences in the non-perturbative hadronization mechanisms in the two kinds of jets.

2 Definition of Sheared Jet and Handedness Observables

2.1 Transverse Spin

Let us consider a transversely polarized jet. A hard jet in this case would result from a quark of transverse polarization, \mathbf{s}_\perp , that emanates from a hard collision. A soft jet would be the beam jet in the collision of a transversely polarized proton of transverse spin \mathbf{s}_\perp with some other particle. (We define a fully polarized proton to have $|\mathbf{s}_\perp| = 1$).

In either case, let \mathbf{t} be the jet axis and consider the distribution of hadrons in the jet as a function of their momentum \mathbf{p} , in particular as a function of the azimuthal angle ϕ of \mathbf{p} about the jet axis. We have a distribution proportional to

$$1 + |\mathbf{s}| \mathcal{A} \cos \phi = 1 + \frac{\mathbf{s} \cdot (\mathbf{t} \times \mathbf{p})}{|\mathbf{p}_\perp|} \mathcal{A}, \quad (1)$$

where $\mathcal{A}(|\mathbf{p}_\parallel|, |\mathbf{p}_\perp|)$ is the left-right asymmetry (or analyzing power) and \mathbf{p}_\perp is the component of \mathbf{p} perpendicular to the jet axis: $\mathbf{p}_\perp = \mathbf{p} - \mathbf{t}(\mathbf{t} \cdot \mathbf{p})$, where we have assumed that \mathbf{t} is a unit vector. The analyzing power \mathcal{A} has a kinematic zero at $\mathbf{p}_\perp = 0$.

The necessity for the above form of asymmetry arises from the facts that spin dependence of a cross-section is linear in \mathbf{s} and that in a parity conserving theory the only scalar quantity we can construct is $\mathbf{s} \cdot (\mathbf{t} \times \mathbf{p})$.

In the case of a soft beam jet, \mathbf{t} is the direction of the incoming polarized proton, and the usual notation is to use A_N instead of \mathcal{A} . Measurements have been made [12, 13] as function of x_F , and reach values of 30% to 40% for $x_F > 0.7$, but are small for $x_F < 0.3$, in the case of charged pions, and somewhat smaller for π^0 .

Collins [4, 5] defined a ‘sheared jet asymmetry’ by exactly the same formula, but applied it to a polarized hard jet, such as would result in deep inelastic lepton scattering (DIS) on a transversely polarized proton. The variable x_F now gets replaced by z —the fractional momentum of the measured hadron in the jet. In the DIS case, the jet axis \mathbf{t} can be defined (in the center-of-mass frame) by parton-model kinematics.

In a more general case one could use a standard jet algorithm to define \mathbf{t} . Alternatively, one can use the 2 leading particles in the jet to define both the jet axis and the azimuthal angle; one replaces $\mathbf{s} \cdot (\mathbf{t} \times \mathbf{p})/|p_\perp|$ by

$$\frac{\mathbf{s} \cdot (\mathbf{p}_1 \times \mathbf{p}_2)}{|\mathbf{p}_1 \times \mathbf{p}_2|}. \quad (2)$$

2.2 Longitudinal Spin

Let us now replace the transverse polarization of the initiator of a jet by a longitudinal polarization (or helicity λ). Then to get a scalar quantity linear in the pseudoscalar λ we need an additional momentum.

One possibility is to have a jet axis and two measured particles:

$$\lambda \mathbf{t} \cdot (\mathbf{p}_1 \times \mathbf{p}_2). \quad (3)$$

This is what is used in the SLD measurement of handedness [11].

A second possibility, the one original given by Nachtmann [1], is to measure three particles in the final state and then we have a possible helicity dependence of the form

$$\lambda \mathbf{p}_1 \cdot (\mathbf{p}_2 \times \mathbf{p}_3). \quad (4)$$

A convenient way to perform a measurement of the dependence of the cross-section on one of these variables is to define

$$\Omega = \mathbf{t} \cdot (\mathbf{p}_1 \times \mathbf{p}_2) \quad (5)$$

for the 2 particle plus jet measurement. Then we define handedness, H , as the asymmetry between the number of events with positive and negative Ω :

$$H = \frac{N(\Omega > 0) - N(\Omega < 0)}{N(\Omega > 0) + N(\Omega < 0)}, \quad (6)$$

where the numbers of events are computed with some suitable cuts on the particles. For example, a minimum p_\perp prevents the value of H from being diluted by the kinematic zero at zero p_\perp , and a minimum x_F or z forces the hadrons to be in the ‘valence region’ where the spin dependence is presumably largest. The results should be presented for H/λ .

The SLD collaboration measured the handedness of jets produced in e^+e^- annihilation at the Z^0 ; where quarks and antiquarks are produced with known, large helicities. The experimenters had to distinguish, in effect, quark and antiquark jets, since their helicities are opposite.

3 Handedness in Soft Jets

3.1 pp and ep experiments

I propose that the handedness of a beam jet be measured in inclusive 2 pion production in relativistic collisions of

$$\vec{p}p \rightarrow \pi^+\pi^-X. \quad (7)$$

Handedness, as defined by Eqs. (5) and (6), is proportional to the helicity λ of the incoming proton; it will reverse sign when λ is reversed. In Eq. (5) we let \mathbf{p}_1 and \mathbf{p}_2 be the momenta of the π^+ and π^- .

Appropriate minima on the values of the transverse and longitudinal momenta of the 2 pions should be imposed. Appropriate values might be $x_{F1}, x_{F2} > 0.3$, $p_{1\perp}, p_{2\perp} > 0.3$ GeV. The only recent experiment that could make the measurement is E704 [12] at Fermilab, but its coverage in azimuth appears to be insufficient to make an analysis of the data worthwhile.

However, the HERMES [14] experiment at DESY is appropriate. It performs collisions of 30 GeV electrons on a polarized gas jet target, so we replace the reaction (7) by

$$\gamma^*\vec{p} \rightarrow \pi^+\pi^-X, \text{ (or equivalently } e\vec{p} \rightarrow e\pi^+\pi^-X), \quad (8)$$

where now we require the measured pions to be in the target fragmentation region. The virtuality of the γ is irrelevant — indeed the closest analogy with the $\vec{p}p$ reaction is at low Q^2 rather than in the deep-inelastic region. Furthermore, to get into the 2-jet region, one should require the hadronic final state to have a high mass — particularly in view of the low energy of the beam. Any polarization of the virtual photon (or of the electron producing it) is irrelevant for our purposes.

Of course, it would also be of interest to measure handedness both for deep-inelastic events and for lower mass final states.

It is desirable to strengthen the cuts on the measured pions to maximize the measured handedness. The need for this is clearly indicated by the way in which the left-right asymmetry in the case of transverse spin rises strongly with x_F and with p_\perp . But one must also make measurements with cuts that correspond to those used by the SLD measurements [11].

3.2 Other Measurements for Soft Jets

To verify that the proton jet in polarized electroproduction behaves like the beam jet in polarized proton-proton scattering, one needs the single transverse spin asymmetry, i.e. the left-right asymmetry in

$$\gamma^* p^\uparrow \rightarrow \pi X. \quad (9)$$

Here the proton is transversely polarized and the pion is in the target fragmentation region. It would require very implausible dynamics for the left-right asymmetry if the results were greatly different from those in pp scattering. In this and other reactions in this paper, we use p^\uparrow , with an upward pointing arrow, to denote a transversely polarized proton, and \vec{p} to denote a longitudinally polarized proton.

In addition, measurements should be made of a two-particle asymmetry with a transversely polarized proton:

$$\gamma^* p^\uparrow \rightarrow \pi^+ \pi^- X. \quad (10)$$

The measurement is of the coefficient \mathcal{A} in

$$1 + \mathcal{A} \frac{\mathbf{s} \cdot (\mathbf{p}_1 \times \mathbf{p}_2)}{|\mathbf{p}_1 \times \mathbf{p}_2|}, \quad (11)$$

where the momentum of one of the measured pions is used instead of the beam axis to define a left-right asymmetry. One should compare this two-particle asymmetry with the conventional one-particle left-right asymmetry. Any dilution of the asymmetry that occurs here by adding an extra particle would likely also occur for hard polarized jets. Compare [4] and [5] for the corresponding definitions for hard jets.

4 Predictions

A hard jet arises when a fast moving quark (or gluon) is created in a short-distance process. The early history of the jet involves quark and gluon radiation governed by perturbative dynamics. The late non-perturbative stages involve an expanded and elongated clump of hadronic matter. In contrast, a soft jet is created by an already extended clump of hadronic matter moving away at high rapidity from a collision.

Thus although the early history of the two kinds of jet is different, it is reasonable to suppose that the non-perturbative part of their hadronization is qualitatively similar, and in particular that the spin effects are similar. On the basis of existing measurements, I predict

- Small handedness (at most a few %) in soft jets.
- Large left-right asymmetries (tens of %) in hard jets at $z > 0.3$ to 0.5.

If this is so, then a nonzero sheared-jet effect should be measurable from current e^+e^- data. This is not an absolute prediction of QCD, since we do not understand its non-perturbative dynamics very well. If, on the contrary, spin effects are substantially different between the

two kinds of jets then that has big implications for models of fragmentation. (There is one obvious difference between soft jets and hard jets at large Q . This is caused by Altarelli-Parisi evolution. Its effects can be minimized by restricting one's attention to clean low multiplicity jets, i.e., ones with little radiation.)

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